3D FE analysis of shot peening of strain-rate sensitive materials Accounting for Multiple and Repeated Impingement

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Abstract This paper is devoted to the investigation of the shot-peening process using 3D finite element (FE) model of multiple impingement. In this analysis, we implement a novel "symmetry cell" approach to examine the impact effect of a large number of rigid and deformable shots on a high-strength steel target made from AISI 4340. Dynamic elasto-plastic simulations were conducted using a rate sensitive material model. A number of convergence tests, which account for element size and stiffness of contact elements, were carried out. In addition, efforts were devoted to determine the appropriate material damping parameters needed to dampen unwanted numerical oscillations associated with the explicit solver of LS-DYNA for this class of problems. The model was used to predict the effect of peening coverage upon the mechanically induced residual stress field for rate sensitive materials under multiple and repeated impacts.

Keywords Shot-peening, Multiple impacts, Residual stress, Finite elements, Rate sensitive

1. Introduction

Shot-peening is a cold-working process accomplished by bombarding the surface of the component with small spherical shots made of hardened cast-steel, conditioned cut-wire, glass or ceramic beads at a relatively high impingement velocity (40–70 m/s). It is used mainly to improve the fatigue life of metallic components [1]. During impingement, a plastic indentation surrounded by an elastic zone is formed. After contact between the shot and the target has ceased, the elastically stressed region tends to recover to the fully unloaded state, while the plastically deformed region sustains some permanent deformation. This inhomogeneous elasto-plastic deformation results in the development of a compressive residual stress field in the exposed upper most layers. To maintain equilibrium in the peened component, a tensile residual stress field is developed in the depth of the component. The mechanically induced surface compressive residual stresses have been found to be highly effective in enhancing the fatigue resistance of critical load bearing components.

The effectiveness of the peening treatment depends, to a large measure, on the peening intensity and the peening coverage. Peening intensity is a measure of the consistency of the treatment and of the plastic dissipation of the impinging shots. Peening coverage, on the other hand, is a measure of the obliteration of the original surface texture and can be defined as the ratio of the area covered by peening indentations to the total exposed surface area. Intensity and coverage depend on numerous variables, including work-piece characteristics, shot characteristics, flow conditions, stand-off distance and exposure time.

Direct residual stress measurements inside the compressed layer are expensive, time consuming, and requires the use of semi-destructive methods. Therefore, the modelling of the shot-peening process has received increasing attention from the scientific community. Several issues have emerged and received extensive investigations about modelling and simulations of multiple impact collisions. The first is concerned with the use of static or dynamic analysis to treat the peening process. Several contributions were made using quasi-static analysis [2-5]. However, some investigations [6-8] have shown that the indentation shape and residual stress distribution caused by static compression are different from those caused by dynamic impact. For example, according to

Kobayashi et al. [8], tensile residual stresses were developed at the centre of the indentation as a result of dynamic impact, while the residual stress caused by static compression is approximately zero at the centre of indentation. Therefore, more realistic approach must be considered to analyze the impact-related phenomena caused by shot-peening. The dynamic modelling of a single shot was initially conducted by Johnson [9] using a pseudodynamic approach, in which only the inertial properties of the shot was taken into account. More work used explicit solvers to model the dynamic process. This includes the contributions made by Klemenz et al. [10], Gariépy et al. [11] etc.

The second issue of simulation is how to model the shot-peening process that involves a large number of impact events. Some authors investigated single or twin shot impacts. For example, Edberg et al. [12] carried out dynamic FE analysis of a single shot on both viscoplastic and isotropic elasto-plastic targets. More and Kulkarni [13], Hong et al. [14] investigated the residual stress patterns from a single shot simulation. Meguid et al. [15,16] examined the effects of shot and target parameters upon the plastic zone development and induced residual stresses from both single and twin shot impacts. Despite the importance of the analysis of single and twin shot impacts to the understanding of the phenomena involved, modelling of the entire peening process should lead to more accurate results. Schiffner and Helling [17] used a simplified approach to model quasi-static target behaviour using time-dependent load functions obtained from the dynamic axisymmetric FE analysis of the impact of a single spherical shot. Their results showed that the influence of adjacent shots cannot be ignored. Meguid et al. [18] developed an enhanced symmetry cell to describe the high-density multiple impacts, and compared the predicted average residual stresses inside the target to experimental measurements using the holedrilling technique. Recently, Mylonas and Labeas [19], Sheng et al. [20] carried out 3D analysis implementing a large number of random shots. Kim et al. [21] investigated the residual stress for multiple shots at oblique impinging angles.

Another issue is to model the effect of the highly localized strain rates involved in the shot-peening process during impingement and rebounding of the jet stream. Some work modeled the target as rate insensitive materials [12,14,16]. However, for many real materials, dynamic analysis accounting for both inertia and rate effects would be essential. Meguid et al. [18] showed that using rate insensitive and rate sensitive material models would lead to different residual stress and plastic strain distributions. Strain rate dependent material was then used to model the target in the work by Kim el al. [21]. In this paper, we provide a 3D FE analysis of shot-peening process using a multiple impingement model for strain-rate sensitive targets and rigid shots. The residual stress distribution was analyzed and the effect of the peening coverage was investigated.

2. Finite element modelling

2.1. Configuration and boundary condition

The investigated situation is that a large number of identical shots impinge a metallic target at normal incidence. In this case, the effect of the boundary of the target can be considered negligible at the centre of the area examined. This has led us to the use of a symmetry cell, which would reduce the modelling considerably. The dimensions of the proposed symmetry cell are $C \times C \times H$, where C is the distance between adjacent shots in one row and H is the cell height, as outlined in Figure 1. The selected cell depth should be large enough to prevent interference from the boundary, while be small enough to maintain reasonable computational time. The single and twin shot impact results published earlier in Refs. [14,16] indicate that a height no smaller than $4R$ is suitable for the different shot velocities examined in these papers. Here R is the shot radius taken as 1.0 mm. For the current multiple-indentation problem $H = 4R$. The distance C can be changed to get different peening intensity.

Symmetry boundary conditions were used at the four side faces of the cell. In addition, all displacements of the cell bottom were restrained. To provide a greater degree of accuracy, full eight-node integration was used. The mesh near the impinging locations was refined. All shots were identically modelled as rigid body discretized using eight-node brick elements with a coarser mesh density. Convergence tests were conducted using different meshes. The convergence test results indicated that the mesh depicted in Figure 1(b) was capable of representing the peening process in a cost-effective manner, as measured by the marginal difference in the maximum residual stress results. Accordingly, this mesh was used for the remainder of the study.

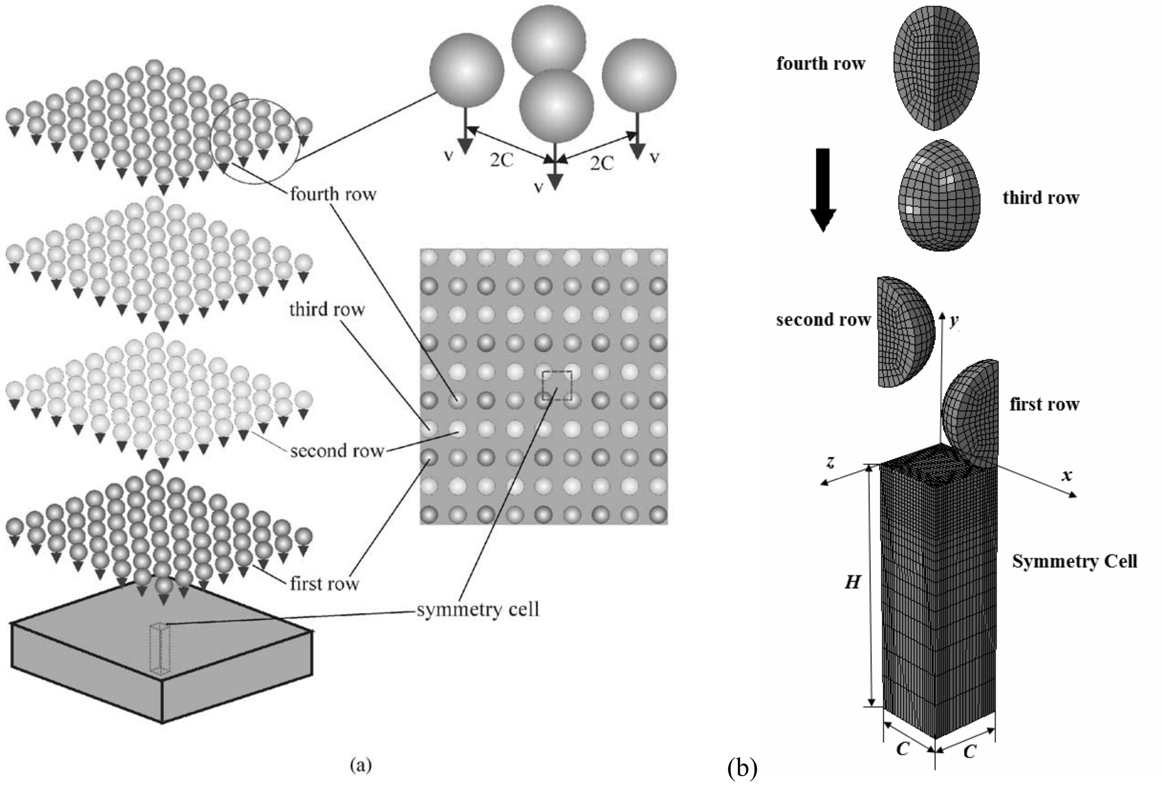
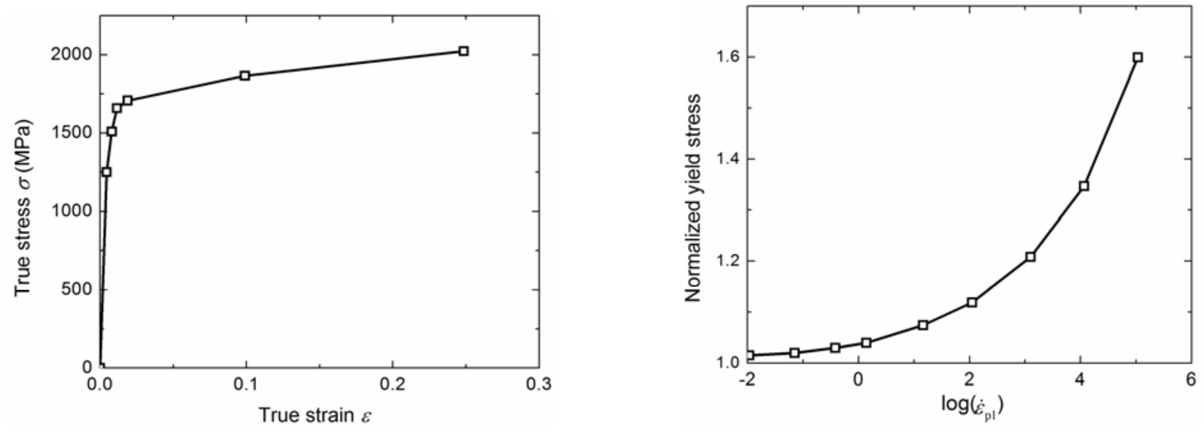


Figure 1. FE multiple impingement model: (a) full model, and (b) discretised symmetry cell.

2.2. Material models

The material of the target was high-strength steel AISI 4340 with density of 7850 kg/m3, which is widely used for shot-peening applications [14,16,18]. A bilinear isotropic hardening elasto-plastic constitutive law was used to model AISI 4340 with Young’s modulus of 205 GPa and Poisson’s ratio of 0.25 [22]. The strain-rate sensitivity was accounted for by using the data developed by Premack and Douglas [22], since they appear to be more reliable and cover a wider range of strain-rate values which are comparable to those observed in shot-peening (up to 10^5 1/s). These data are incorporated in the FE model by scaling the quasi-static stress–strain curve for different strain rates according to [22]. The shots were made of high carbon steel with the density assumed as being 7850 kg/m3.



(a) (b)

Figure 2. Stress–strain relationship for AISI 4340 steel [22]: (a) quasi-static uniaxial stress–strain curve, and (b) the normalised effective yield stress accounting for strain-rate sensitivity.

2.3. Simulation procedure

The peening treatment of the cell was simulated by the impingement of rows of identical shots with a symmetric layout inside each row. These rows are further combined in series of four rows each. To achieve higher peening coverage, each subsequent row in the series is shifted laterally so that the shots in this row impinge different areas of the target symmetry cell as shown in Figure 1. To achieve higher peening intensity, several series of shot rows were used to impact the cell. A total of four series was used, which brings the total number of shot rows to 16.

The 16 shots were impinging to the target surface of the symmetry cell one by one as shown in Figure 1(b). The impinging velocity was unanimously chosen as 75 m/s in this study. A time interval of 10 ms was chosen between subsequent impacts. It is necessary to introduce material damping in order to prevent unnecessary long post-impact residual oscillations. If these oscillations are not reduced significantly prior to the following impingement taking place, they could accumulate leading to numerical instability. However, care must be taken so that the introduction of this damping should not disturb the solution. The material damping was introduced as being Eq. (1).

$$D = \alpha M + \beta K , \qquad (1)$$

Where D, M and K are the damping, mass and stiffness matrices, respectively. As a result of a number of trial runs, it was determined that effective damping can be achieved using a stiffness proportional damping coefficient β = 2 x 10^{-9} s. To obtain reliable values of mass proportional damping α the following approach was adopted. For the given symmetry cell, the minimal modal frequency ω_0 could be estimated as in Eq. (2).

$$\omega_0 = \frac{1}{H}\sqrt{\frac{2E}{\rho}} , \qquad (2)$$

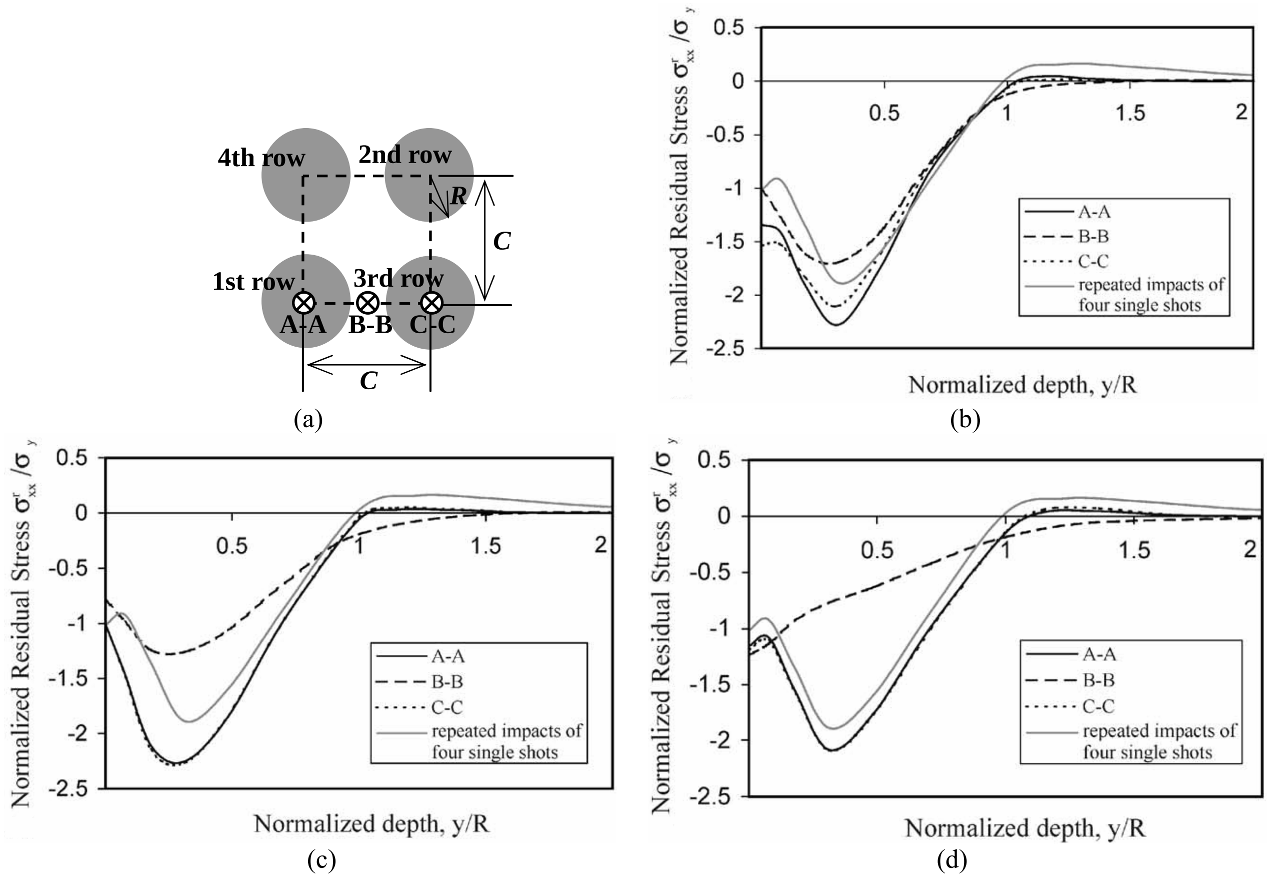
Where E is the target Young's modulus, ρ is its density and H is the height of the symmetry cell. The mass proportional damping is then determined as in Eq. (3).

$$\alpha = 2\omega_0\xi , \qquad (3)$$

Where ξ is the corresponding modal damping parameter. In this study, ξ was selected as 0 during the impact stage and changed to 0.5 between subsequent shot impacts to decay the unwanted low-frequency oscillations.

3. Results

The FE model was developed using the explicit commercial finite element code ANSYS/LS-DYNA version 13. In contrast to the single shot impact, the current model is capable of modelling the effect of peening coverage. This was achieved by varying the separation distance C between adjacent shots. Figure 3 shows the residual stress distribution along the target depth direction. The residual stress σ_{xx} is plotted versus the target depth at three locations A–A, B–B and C–C as indicated in Figure 3(a). Three normalized separation distances were investigated as shown in Figures 3(a)–(c), respectively for C/R=1, 1.5 and 2. The corresponding stress distribution beneath the centre-line after repeated impact of four subsequent shots that hit the target in the same place is also provided for comparison. The results show that multiple shot impacts lead to interaction between the unloading residual stress fields resulting from individual impacts. This interaction effects lead to a much more uniform distribution of residual stresses along the target surface and subsurface regions than the results of single and twin shot impact models. As expected, the decrease in the separation distance leads to a more uniform residual stress distribution across the target as can be seen from the smaller distinction between the three curves of different locations. This is attributed to stronger interaction between individual shot impacts. The average depth of the compressed layer increases with the decrease in the normalized separation distance. However, the maximum values of the compressive residual stress are comparable for all the three cases examined. For separation distance $C/R \geq 2$, the residual stress distributions beneath the shot corresponding to the multiple impingement model are very close to those of the repeated impact sequence of four coincident shots.



(a) (b)

(c) (d)

Figure 3. Effect of separation distance C/R upon residual stress distributions along target depth direction at three locations as indicated in (a) after rebound of fourth series (16 row) of shots: (b) C/R=1, (c) C/R=1.5, and (d) C/R=2. Also compared is the distribution along the center line for the case of four subsequent shots hitting the target at the same place.

4. Conclusions

A comprehensive 3D dynamic elasto-plastic finite element analysis was conducted to simulate the shot-peening process using rate sensitive targets, multiple and repeated impingements. The mechanically induced residual stress distributions were examined using a representative symmetry cell. It indicated that multiple shot impacts resulted in a more uniform residual stress at and immediately beneath the exposed surface layers compared to single and twin shot impacts. The separation distance between shots influences the residual stress field significantly. The decrease in separation distance leads to a more uniform residual stress distribution in the treated target. The average depth of the compressed layer increases with a decrease in the normalized separation distance C/R from 2 to 1. However, the maximum value of the compressive residual stress and plastic strain fields are comparable for all the three cases examined. For separation distances $C/R \geq 2$, the interaction between different shot impacts along the target surface are negligible.

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